

Practical Application of the Hole Expansion Test

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ABSTRACT

Until now the hole expansion ratio has been generally regarded as a relative “local formability” parameter with limited application to edge-cracking analysis and prediction. In this study a constrained statistical test data analysis methodology is introduced, where the lower-bound hole expansion ratio is the basis for three practical edge-cracking failure criteria. The Maximum Edge Stretch Criterion is directly compatible with CAE simulation. The Edge Thinning Limit Criterion and the Critical Thickness Criterion are more useful in field work and post mortem laboratory failure analysis. Two case studies are described, where hole expansion test data are used to analyze edge cracking of Advanced High Strength Steel (AHSS) in real-world automotive seating applications. Finally the intrinsic local and global formability parameters of the subject AHSS materials were explored, and a linear relationship between the hole expansion ratio and reduction of area at fracture in tension was demonstrated.

CITATION: Hance, B., "Practical Application of the Hole Expansion Test," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-0306.

INTRODUCTION

Hole Expansion (HE) Test Procedures

The purpose of the hole expansion (HE) test is to assess edge stretching performance of sheet metals, where a punch is forced through a prepared hole until edge cracking occurs. Initial hole diameters, edge conditions and HE punch configurations vary. Most commonly, edge stretching performance is measured with the conical-punch HE test according to ISO Standard 16630 [1]. The ISO standard is based largely upon the original 1996 JFS Standard T 1001-1996 [2]. The basic test methodology is to expand a 10 mm diameter hole with a 60° conical punch while clamping the test specimen with enough force to prevent draw-in. The hole expansion test is stopped when a through-thickness edge crack is detected visually. The limiting ratio of the increase in hole diameter to the original hole size (or “hole expansion ratio”) is

$$\lambda, \% = 100 \left(\frac{D_f - D_o}{D_o} \right) \quad (1)$$

Where D_o and D_f are the initial and final specimen hole diameters, and λ is the hole expansion ratio. D_f is the average of two perpendicular caliper measurements [crack location(s) avoided].

HE Test Specimen Preparation

Holes are pierced with 12% nominal clearance according to ISO Standard 16630, with clearance (c) defined as:

$$c, \% = 100 \left(\frac{d_a - d_p}{2t} \right), \quad (2)$$

where d_a and d_p are the piercing die and piercing punch diameters, and t is the sheet thickness. Here, d_p is held constant at 10.0 mm, and d_a is chosen to achieve the desired clearance (0.1 mm diameter increments). ISO Standard 16630 covers the thickness range from 1.2 mm to 6 mm inclusive and mandates that $c = 12 \pm 2\%$ for $t < 2$ mm and $c = 12 \pm 1\%$ for $t \geq 2$ mm. ISO Standard 16630 also mandates that HE tests be run in the “burr up” configuration-*i.e.* the burr faces away from the conical punch.

HE Testing Concerns

Hole expansion testing is fraught by excessive uncertainty and variation, and the results of which can be heavily influenced by specimen preparation technique and human subjectivity. For example in 2013, a group of European steel researchers [3] reported “an unacceptably large difference between labs” with reference to the ISO Standard 16630 HE test. They ultimately concluded that the “difference is too large for the method to be useful in practice.” It was also shown that inter-laboratory differences may be reduced if the number of test specimens is increased from three to ten; however, intra-laboratory scatter remained large.

The hole expansion ratio (λ) is generally regarded as a relative “local formability” parameter with limited application to edge-cracking analysis and prediction. By the very nature of the hole expansion test, λ represents a condition *beyond* failure and has little meaning as a practical failure criterion. However, with a few assumptions and a simplified statistical analysis approach, hole expansion test data may be transformed into useful failure criteria for CAE simulation, field work and laboratory analysis.

BACKGROUND

In the following a data analysis methodology is described, where a constrained statistical approach is used to identify hole expansion (HE) test data outliers. Hypothetical datasets are used to illustrate and classify the various distributions that are likely to be encountered during HE testing. Additionally, three practical failure criteria based on the lower-bound hole expansion ratio are introduced.

Data Analysis Methodology

Preface

Figure 1 shows five hole expansion test data distributions for five hypothetical materials. For each material, the average (mean) λ value (μ_λ) is 30.0% ($n = 5$); however, the datasets are clearly different. If a sixth specimen were to be tested for each material, the expected λ value for the sixth test would also be different in each case. Intuitively, one might expect a λ value around 30% for Material A (Grouped) and Material C (Grouped Middle). Also intuitively, a λ value as low as 15% or as high as 45% should be no surprise for Material B (Dispersed). Similarly, λ values just above 30% and just below 30% might be expected for Material D (Grouped High) and Material E (Grouped Low), respectively.

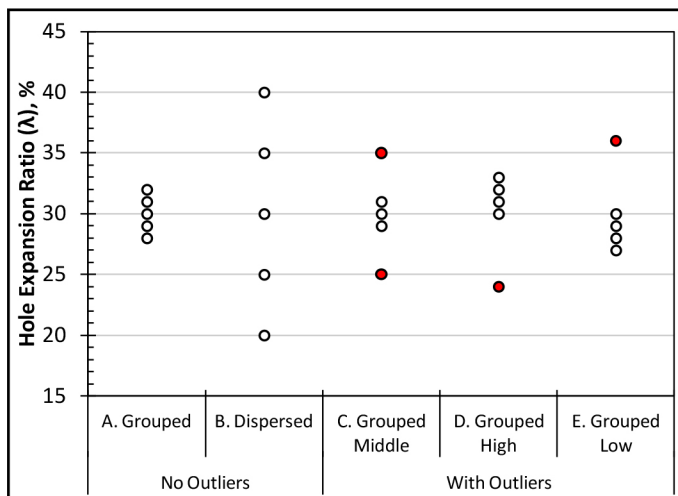


Figure 1. Five hypothetical hole expansion test distributions ($\mu_\lambda = 30.0\%$); Filled symbols represent statistical outliers; See text for details

For this hypothetical illustration, datasets of five test results ($n = 5$) were chosen for the following reasons:

- ISO Standard 16630 [1] mandates that at least “three tests shall be carried out.”
- It is desired to have the flexibility to identify statistical outliers from erratic datasets.
- Given the nature of fracture and the nature of the hole expansion test method itself, both low and high outliers are possible.
- A dataset of five values ($n = 5$) is the smallest dataset that would allow for the identification and omission of low and high

outliers (one or the other, or one of each, if applicable) while still satisfying the above ISO requirement ($n \geq 3$).

- From a statistical perspective, a larger number of test specimens is better (five is better than three); however, from a resource perspective, a lower number is better (five is better than ten).

Outliers

To determine outliers, a constrained statistical approach is used. First, a normal distribution is assumed, and second, the five λ values are sorted from lowest to highest (λ_1 through λ_5). Once the data are sorted, the second-lowest value (λ_2) is assumed to be the 25% quartile (Q_1), and the second-highest value (λ_4) is assumed to be the 75% quartile (Q_3). The inter-quartile range (IQR) is therefore

$$IQR = Q_3 - Q_1 = \lambda_4 - \lambda_2. \quad (3)$$

Low and high outliers may be identified by their relative positioning with respect to statistical “fence posts”, where the left fence post (LFP) and right fence post (RFP) are commonly defined as

$$\begin{aligned} LFP &= \lambda_2 - 1.5(IQR) \\ RFP &= \lambda_4 + 1.5(IQR), \end{aligned} \quad (4)$$

and it follows from Equation 3 and Equation 4 that

$$\begin{aligned} LFP &= \lambda_2 - 1.5(\lambda_4 - \lambda_2) \\ RFP &= \lambda_4 + 1.5(\lambda_4 - \lambda_2). \end{aligned} \quad (5)$$

If the minimum measured λ value lies to the “left” of the left fence post ($\lambda_1 < LFP$), it is considered a low outlier and may be discarded. Similarly, if the maximum measured λ value is to the “right” of the right fence post ($\lambda_5 > RFP$), it may be discarded. These relationships are shown schematically by example in Figure 2 where λ_1 was deemed an outlier, and λ_5 was determined not to be an outlier-*i.e.* Distribution Type D in Figure 1. For this example the mean λ value (μ_λ) should be recalculated with the outlier omitted (μ_λ') by averaging the four largest λ values (λ_1 excluded). Unless otherwise mandated, μ_λ' may be considered the average hole expansion ratio; however, for practical use in edge fracture analysis and prediction, a lower-bound approach may be used.

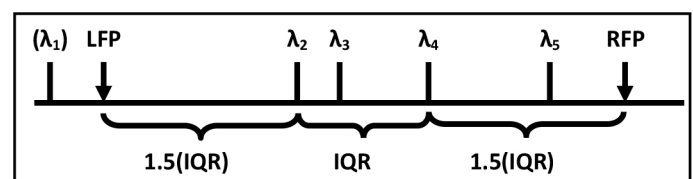


Figure 2. Schematic representation showing the relationships between HE test data (λ_1 through λ_5), the inter-quartile range (IQR), and the left and right fence posts (LFP, RFP); See text for details

Lower-Bound Hole Expansion Ratio

For a normal distribution, the widely known “68-95-99.7 rule” refers to percentages of values that lie within a band centered on the mean (μ) with band-widths of $\pm 1\sigma$, $\pm 2\sigma$, and $\pm 3\sigma$, respectively. More precisely, this rule may be expressed as the following probabilities:

- $\Pr(\mu - 1\sigma \leq x \leq \mu + 1\sigma) \approx 0.6827$
- $\Pr(\mu - 2\sigma \leq x \leq \mu + 2\sigma) \approx 0.9545$
- $\Pr(\mu - 3\sigma \leq x \leq \mu + 3\sigma) \approx 0.9973$

where $\Pr$ is a probability function, and x is an observation from a normally distributed random variable [4]. Furthermore, the “three-sigma rule of thumb” is the notion that 99.7% probability may be regarded as near certainty. In the context of hole expansion testing, one may expect nearly all test values to lie within the range: $\mu_{\lambda}' - 3\sigma_{\lambda}' \leq \lambda \leq \mu_{\lambda}' + 3\sigma_{\lambda}'$. Therefore, a practical lower-bound hole expansion ratio is

$$\lambda_{LB} = \mu_{\lambda}' - 3\sigma_{\lambda}' \quad (6)$$

where μ_{λ}' and σ_{λ}' are the mean and standard deviation of the hole expansion ratio (outliers removed), and λ_{LB} is the lower-bound hole expansion ratio. From the symmetry of a normal distribution, the “68-95-99.7 rule” becomes the “84-98-99.9 rule” for lower-bound values. In terms of probabilities:

- $\Pr(\mu - 1\sigma \leq x) \approx 0.8414$
- $\Pr(\mu - 2\sigma \leq x) \approx 0.9772$
- $\Pr(\mu - 3\sigma \leq x) \approx 0.9986$.

So, in other words, for a given sample, 999 out of 1000 measured λ values would be expected to be greater than λ_{LB} . As a further illustration, the hypothetical datasets from Figure 1 are listed in Table 1, and the λ_{LB} values are calculated for each distribution type. These results are also shown graphically in Figure 3.

Table 1. Hypothetical HE Test Datasets (outliers in parentheses)

Distribution Type→		No Outliers		With Outliers		
λ	λ_1	28	20	(25)	(24)	27
	λ_2	29	25	29	30	28
	λ_3	30	30	30	31	29
	λ_4	31	35	31	32	30
	λ_5	32	40	(35)	33	(36)
μ_{λ}		30.0	30.0	30.0	30.0	30.0
σ_{λ}		1.6	7.9	3.6	3.5	3.5
Q_1		29	25	29	30	28
Q_3		31	35	31	32	30
IQR		2.0	10	2.0	2.0	2.0
LFP		26	10	26	27	25
RFP		34	50	34	35	33
μ_{λ}'		30.0	30.0	30.0	31.5	28.5
σ_{λ}'		1.6	7.9	1.0	1.3	1.3
λ_{LB}		25.3	6.3	27.0	27.6	24.6

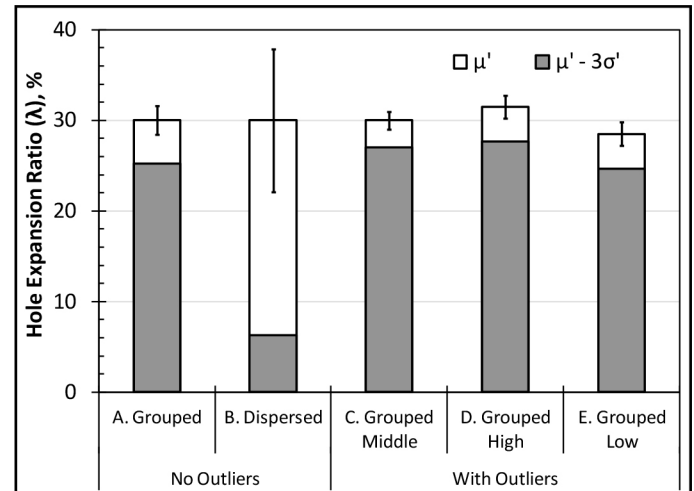


Figure 3. Graphical summary of the analysis shown in Table 1; Here, μ' and σ' are the mean hole expansion ratio (μ_{λ}') and standard deviation of λ (σ_{λ}') with outliers removed (if applicable); Error bars indicate $\pm 1\sigma'$

The absence of outliers may be a positive or negative reflection on the *quality* of the dataset. It could mean that the all data are tightly grouped (*i.e.* well behaved), or it could mean that the data are simply too erratic to exclude any values as outliers. The former case is clearly the preferred case (Type A: Grouped), while the latter case is the most problematic (Type B: Dispersed). For a Dispersed distribution additional testing may help ($n > 5$) or the entire dataset may be discarded with another set of five specimens re-tested and analyzed in the same way. Furthermore, the distinction between a Grouped distribution and a Dispersed distribution is rather more intuitive than it is fact-based. The distinction lies in the relative preponderance of the IQR value with respect to the mean value. For example, in Table 1, the IQR value of Distribution Type A is less than 7% of the mean value, while that of Distribution Type B is one-third of the mean value. Similarly, Distribution Types C through E may also be considered “well-behaved”, albeit with outliers. Outliers are discussed further in Case Study I.

Maximum Edge Stretch Criterion

The maximum edge stretch (e_{max}) is equivalent to the lower-bound hole expansion ratio:

$$e_{max}, \% = \lambda_{LB} \quad (7)$$

In terms of true strain, Equation 7 may be written as

$$\epsilon_{max} = \ln \left[1 + \frac{\lambda_{LB}}{100} \right] \quad (8)$$

This simple criterion predicts that edge cracking will be averted if the maximum principal strain at the sheared edges of a formed component is kept below ϵ_{max} . The maximum edge stretch criterion is directly compatible with CAE formability simulation and may also have limited use in the analysis of gridded parts in stamping trials. Note that Equation 7 assumes good-quality blank edges.

shearing clearance per ISO Standard 16630). The most appropriate value of $e_{\max}$ might be higher than λ_{LB} (e.g. laser cutting) or lower than λ_{LB} (i.e. poor sheared-edge quality).

As mentioned in the Introduction, λ represents a condition beyond failure; however, λ_{LB} represents a conservative value that is well-below the average hole expansion ratio. Furthermore, near fracture sites on HE test specimens, local strains could be higher than the average value represented by λ , and thus, any failure criterion based on λ_{LB} may be considered doubly conservative.

Edge Thinning Limit Criterion

Another useful failure criterion derived from hole expansion test data is the edge thinning limit (ETL) [5]. The edge thinning limit is defined as

$$ETL, \% = 100 \left(1 - \exp \left[\frac{-\ln \left(1 + \frac{\lambda_{LB}}{100} \right)}{R_m + 1} \right] \right), \quad (9)$$

where R_m is normal anisotropy measured in tension. Like the Maximum Edge Stretch Criterion (Equations 7 and 8), the ETL criterion may be used in CAE formability simulation. In this case, if the “percent thinning” exceeds the ETL anywhere along the edge of a deformed blank, a risk of edge-cracking is predicted. Again, the ETL value applies only to blanks with edge condition similar to that maintained during hole expansion testing.

The key to understanding the relationship between hole expansion and edge thinning is to recognize that the stress state near the edge of an expanding circular hole is approximately uniaxial tension. A derivation for the edge thinning limit (Equation 9) is given in the Appendix.

Critical Edge Thickness Criterion

For field work and postmortem laboratory analysis, the edge thinning limit may be converted to a critical edge thickness value (t_c) based on the original thickness (t_o), where

$$t_c = t_o \left(\frac{100 - ETL}{100} \right). \quad (10)$$

This criterion predicts a risk of edge-cracking if the measured thickness is below t_c near the edge of a formed component. The original thickness (t_o) should be measured with a micrometer on a flat blank or sheet from the same lift or coil as the component of interest, if possible. If no such reference thickness value is available, the nominal thickness value may be used with caution.

Non-Destructive Analysis

Once t_c is determined, edge thickness measurements may be made with a ball-tipped or point-tipped micrometer in areas of interest. Flat-faced micrometers should never be used for this purpose (burrs

and/or part curvature may result in artificially high local thickness readings). Taking thickness measurements with a micrometer near the edge of a formed component is tricky, and results can vary considerably between operators. This method is generally not recommended; however, it may be used as a “quick check” method to see how near a component is to reaching its critical edge thickness. This method of edge fracture analysis is featured in Case Study II.

Destructive Analysis

If permissible and practical, edge thickness measurements should be made by carefully sectioning the component and preparing the edge for metallographic examination in cross-section. Again this procedure can be tricky if the edges are curved-e.g. at the edge of an expanded hole. The assistance of a skilled metallographer should be employed for specimen preparation. Thickness measurements may be made with a calibrated microscope and image analysis software or may be estimated from micrographs containing scale markers or “micron bars”. As a rule of thumb, thickness measurements should be made at a distance equal to the original thickness (t_o) from the edge to avoid the shear-affected zone (SAZ) on a sheared edge, for example. This method of edge fracture analysis is featured in Case Study I.

CASE STUDY I

Overview: Case Study I

An eight-station automotive seat component stamping progression was submitted to the U. S. Steel Automotive Center Laboratory for analysis related to a reported edge-cracking condition. Edge-cracking occurred at the fourth progression station. The material in question was a cold-rolled dual-phase advanced high strength steel with 780 MPa minimum tensile strength (DP780). Basic tensile properties of the subject material are given in Table 2. Duplicate ASTM standard specimens were tested in the transverse (T) orientation (90° from the rolling direction) [6].

Table 2. Tensile Properties*: Case Study I

Material	t, mm	YS, MPa	UTS, MPa	UE, %	TE, %
DP780	2.0	523	799	9.5	17.0

*Each value represents the average of two specimens

Upon examining the cracked component, mild burrs and an intermittent “scallop” pattern were noted on the otherwise normal-looking sheared edges. The component was sectioned both away from the edge crack and near the edge crack. The deformed edges were mounted in cross-section and prepared for metallographic examination. Images in the polished-and-etched condition are shown in Figure 4 (“burr down” orientation), and characteristic “rollover” and microstructural flow patterns associated with a sheared edge were still apparent after forming.